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Whither Design Theory and Methods?

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Abstract: This position paper briefly introduces design theory and design methods, presents changes that have occurred on the last 50 years prior to examining the changes that are likely to take place over the next 50 years in designing and in building. It examines potential changes in our knowledge about the cognitive behaviour of designers, users, users' social behaviour, user-building interactions, user emotions, design tools that learn and adapt, buildings that learn and adapt, buildings as part of a social ecology, and three new types of interfaces: brain-computer interfaces, user-building interfaces and brain-building interfaces. Each of these is assessed for their potential effect on design theories and design methods. The conclusion is that very few, if any, of these will require modifications to design theories but that new design methods will need to be developed.

Keywords: Design theory; design methods

1. Introduction

Design methods date back at least 4,000 years to the instructions for a flood-proof ark given in the *Epic of Gilgamesh* and the rules for urban design given in the *Instructions of Shuruppak*. Some 500 years later design and building are given a unique mention in the *Code of Hammurabi.* The history of architecture gives special attention to the design rules in Vitruvius' *De architectura: Ten Books of Architecture*, which dates from 50 BC. Vitruvius gave both prescriptive and performance design methods in the form of rules. However, it was not until 1452 that Leon Battista Alberti in his *De re aedificatoria: Ten Books of Architecture,* introduced the concept of design process as an intellectual activity that involved a designer and which laid the foundation for design theory. Alberti also laid the foundation for two separate streams of enquiry: design as a process and design as an object. Modern scientific-based design research leading to more formal design theories and design methods commenced in Germany in the 1850s with Ferdinand Redtenbacher, who in 1841 became the Professor in Mechanics and Mechanical Engineering at the Polytechnikum Karlsruhe. He propounded the view that design could become a science. Franz Reuleaux, who studied under Redtenbacher and became a Professor of Engineering at the Swiss Federal Institute in Zurich took that view further with the formalization of the kinematics of machines. At the same time, also in Germany, there was the view that not all of designing could scientized and that some aspects of designing were humanist in nature and hence beyond the purview of formalized methods.

Research in design as a process in the second half of the 20th century began in the 1950s with one of the first conferences on design methods being held in 1962 resulting in the influential *Conference on Design Methods: Papers presented at the conference on systematic and intuitive methods in engineering, industrial design, architecture and communications* (Jones and Thornley, 1963). One of the early and seminal books in architecture was Christopher Alexander's *Notes on the Synthesis of Form* (Alexander, 1964) although similar research in engineering design appeared before Alexander (Asimov, 1962). However, the more widely read and more influential book was the result of Herbert Simon's Karl Compton Lectures at MIT in 1967 that he turned into the book *The Sciences of the Artificial* (Simon, 1969) which lead to a noticeable increase in both research and research funding in Australia, the USA and the UK for design methods and design theory.

We can place research in design as a process over the past 50 years into the following categories: design using simulation, design using optimization, design using artificial intelligence and design using cognitive science. Research in design as an object in the second half of the 20th century began in architecture (and engineering) with the development of formal models of representation of objects, primarily in PhD theses produced at Cambridge and Stanford Universities in the 1960s and 1970s. This has resulted in CAD systems with varying degrees of modeling capabilities. Most recently there has been a confluence of these two streams through the use of visual programming languages such as Grasshopper that not only parameterize object modeling but also allow for the inclusion of simulation and optimization during modeling (Tedeschi, 2011; Woodbury, 2010).

In line with the theme of the conference this paper discusses two questions:

- What has happened to design theories and methods over the last 50 years?
- Will design theories and methods change over the next 50 years?

The next section of the paper briefly describes the development and changes to design theories and presents an example of one that is presented in the form of an ontology that is used as a frame of reference for later discussions in the paper. This is followed by a section that briefly describes umbrella design methods in use today. We then turn to the areas that are harbingers of change and are likely to play an increasing role in designs and designing and examine whether they require changes to design theories and design methods.

2. What has happened to design theories over the last 50 years?

Design research has largely adopted the scientific paradigm in which it is assumed that there are regularities that underlie phenomena and it is the role of research to discover and represent those regularities in designs and designing. When the representation of those regularities has the capacity not only to describe the past and to account for the present but also to predict we claim that it is a theory. Goel and Helms (2014) state that "a scientific theory is (i) based on testable hypotheses and makes falsifiable predictions, (ii) internally consistent, (iii) supported by evidence, and (iv) modifiable as new evidence is collected". Any general design theory commences with or can be based on the following qualitative axiom:

> *The foundations of designing are independent of the designer, their situation and what is beingdesigned* (Gero and Kannengiesser, 2014).

A model of designing is "a representation of some phenomena and relationships among phenomena … [whilst] a theory is an abstract generalisation of phenomena, which can be modelled in multiple ways."

(Chakrabarti and Blessing, 2014, p. 29). Designing, including designing in architecture, for the last 50 years has until recently been a manual act carried out by individuals and teams. The design theories were based on experience (Pahl and Beitz, 1983), induction over cases (Altshuller, 1984; Gero, 1990), or formal derivations from axioms, logic or mathematics (Braha and Maimon 1998; Hatchuel and Weil, 2003; Suh, 2001). Many models of designing can be traced to Asimov (1962).

The environment of designing has changed with the introduction of novel technologies for both designing and for what is being designed. An examination of design theories (Chakrabarti and Blessing, 2014) does not show that there has been a consequential change due to what is being designed. Empirical studies have shown that the same theoretical framework could be applied to novel areas such as software design as to traditional areas such as architecture and engineering. One such theory is based on using the Function-Behaviour-Structure (FBS) ontology as a theory (Gero, 1990; Gero and Kannengiesser, 2014).

We will use this as an exemplary design theory in this paper and base our examination of the need for change in a design theories on the capacity of this design theory to cover potential future changes in the what is to be designed. Hence, we present it in sufficient detail for later use. The FBS ontology is a design ontology that describes all designed things, or artefacts, irrespective of the specific discipline of designing. Its three fundamental constructs – function (F), behaviour (B) and structure (S) – are defined as follows: *Function* is the teleology of the artefact ("what the artefact is for"). It is ascribed to the artefact by establishing a connection between one's goals and the artefact's measurable effects. *Behaviour* is defined as the artefact's attributes that can be derived from its structure ("what the artefact does"). Behaviour provides measurable performance criteria for comparing different artefacts. *Structure* is defined as its components and their relationships ("what the artefact consists of").

Humans construct connections between function, behaviour and structure through experience and through the development of causal models based on interactions with the artefact. Specifically, function is ascribed to behaviour by establishing a teleological connection between the human's goals and the observable or measurable performance of the artefact. Behaviour is causally connected to structure, i.e. it can be derived from structure using physical laws or heuristics. There is no direct connection between function and structure except through experience. For a more detailed exposition of the FBS ontology consult Gero and Kannengiesser (2014).

The most basic view of designing consists of transformations from function to behaviour, F $\rightarrow$ B, and from behaviour to structure , B $\rightarrow$ S. view, behaviour is interpreted as the performance expected to achieve desired function. Yet, once a structure is produced, it must be checked whether the artefact's "actual" performance, based on the structure produced and the operating environment, matches the "expected" behaviour. Therefore, the theory based on FBS distinguishes two classes of behaviour: expected behaviour (Be) and behaviour derived from structure (Bs). This extends the set of transformations with which we can describe designing to include: F $\rightarrow$ Be, Be $\rightarrow$ S, S $\rightarrow$ Bs, and Be $\leftrightarrow$ Bs (comparison of the two types of behaviour). The observable input and output of any design activity is a set of requirements (R) that come from outside the designer and a description (D) of the artefact, respectively. The FBS framework subsumes R in the notion of function and defines D as the external representation of a design solution, S $\rightarrow$ D.

Based on the common observation that designing is not only a process of iterative, incremental development but frequently involves focus shifts, lateral thinking and emergent ideas, the theory defines the following additional transformations, S $\rightarrow$ S', S $\rightarrow$ Be', and S $\rightarrow$ F (via Be). These three transformations assume an existing structure as the driver for generating changes in structure, behaviour or function.

The eight fundamental transformations or processes in the theory are shown and labelled in Figure 1: 1. Formulation (R → F, and F → Be); 2. Synthesis (Be → S); 3. Analysis (S → Bs); 4. Evaluation (Be ↔ Bs); 5. Documentation (S → D); 6. Reformulation type 1 (S → S'); 7. Reformulation type 2 (S → Be); 8. Reformulation type 3 (S → F).

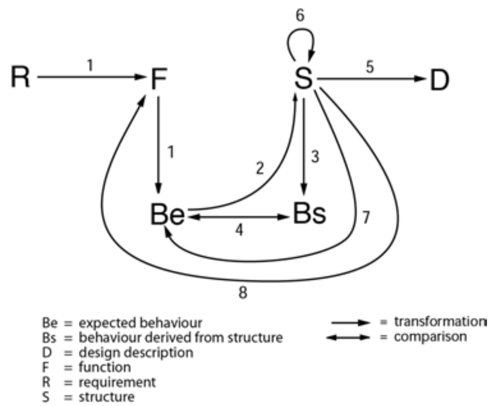

Figure 1: A theory of designing based on the FBS ontology. (Source: Gero and Kannengiesser, 2014)

New areas of knowledge have developed over the last 50 years. Of particular interest to design researchers is cognitive science, which studies the processes of the mind. The knowledge produced by cognitive science has had an effect on design theories in that some have been extended to include cognitive behaviour without changing the underlying concepts such that the cognitive design theory maps onto the earlier theory when removing cognitive behaviour.

Using the exemplary design theory shown in Figure 1, cognitive science distinguishes between the mind (inside the designer's head) and what is external to the designer's mind. The FBS theory needed to be extended to include this distinction and as a consequence new cognitive processes that were not in the original formulation were added. The resulting ontology on which the design theory was now based is labeled the situated FBS ontology. It is founded on idea that situated designing involves interactions between three worlds: the external world, the interpreted world (inside the designer's mind) and the expected world (also (inside the designer's mind) (Gero and Kannengiesser, 2004). However, the foundational ontology is unchanged.

3. What has happened to design methods over the last 50 years?

Design methods, the techniques and tools used to design, have changed with the introduction of new designing technologies although the fundamental processes of designing have not. Here we will give some examples demonstrating this. Optimization as a design method is a formal process that requires a set of design variables, a set of equations that describe the constraints on the values those variables can take and a relationship between the design variables that needs to maximised or minimised. (Papalambros and Wilde, 1988; Radford and Gero, 1988). This fits within the theoretical design process of "synthesis" and therefore does not require any modification of the theory. However, it does require that the designer change the way they design by defining all the design variables at the outset of the optimisation process. As a second example of a novel design method consider design using evolution. Here the design method is a form of search that is based on a simplified genetic model of Darwin's Theory of Evolution (Bentley, 1999). Again all the design variables need to defined at the outset as does the search criterion. The design variables are represented as genes, along with a mapping from the genes to the design and a derivation of the performance from the design. The genetic operators of crossover and mutation are used to move around the design space and are applied in parallel to a population of designs. The performance of the individual designs generated are used to rank the designs in that generation for selection to be used as the basis for the next generation. This fits within the theoretical design process of "synthesis" and therefore does not require any modification of the theory. However, it does require that the designer change the way they design by defining all the design variables at the outset when applying this method. As the third example consider parametric design exemplified by Grasshopper used with Rhino (McNeel, undated). Grasshopper is a visual scripting language that works with parameterised variables (Tedeschi, 2011; Woodbury, 2010). Yu et al (2015) have shown that existing design theories can be used to elucidate explanations of empirically observed design methods as well as describe cognitive behaviour (Yu et al, 2013).

4. What is likely to happen in the future and its effects on design theories and design methods?

Here we list and some of changes that are likely to happen in the future and the effects they may have on design theories and methods.

4.1. Cognitive behaviour of designer

Currently only a small number of design theories take account of the designer's cognitive behaviour, while no account is taken of their behaviour in almost all design methods. The situated FBS theory is an example of a design theory that has changed with the change in available knowledge about designers (Gero and Kannengiesser, 2004). New knowledge about human thinking is likely to have an impact on both theories and methods (Haselton et al, 2015; Kahneman, 2011; Lawson, 1990). Kahneman's System 1 and System 2 Thinking has the potential to describe a range of observed design behaviours including fixation, design patterns, and divergence and convergence. This is likely to result in novel cognitively-based design methods. We can already see "cognitive computing" becoming a new research and application area (IBM, 2017) with potential to be used in novel design methods. We can expect that the design process may include how the designer is progressing towards a design and provide feedback to the designer using concepts from information theory in meta-models of the designer's cognitive space of potential designs (Shannon, 1948). This fits into some existing design theories such C-K theory (Hatchuel and Weil, 2003) and FBS (Gero, 1990) but not axiomatic design theory (Suh, 2001).

4.2. Users

Currently modelling of the building's behaviour rarely includes modelling the behaviour of people in the building, although there is a rich field modelling user-device behaviours (Preece et al, 2015). This is generally left to post-occupancy evaluation and is not part of the design process (Preiser et al, 1990). We can expect to see design simulation methods that include occupants' and visitors' use of the building as part of the design process (Bona and Salotti, 2014; Preiser et al, 2015; Tsai and Gero, 2006). Since the modelling of user behaviour is a form of *analysis* it fits well into current theories of design and therefore does not require any modifications to existing design theories. It may require new methods to carry out the modelling (Schaumann et al, 2015).

4.3. Users' Social Behaviour

Increasingly we live in world that uses social media as the connective tissue between people and their environments (Lenhart et al, 2010; Stefanidis et al, 2013). The social behaviour of building occupants needs to be accounted for in any method. Users' social behaviour is different to users' behaviour as an individual's behaviour is modified by the behaviour of other users through social media. This is an underexplored area in design research although it has become a major research area in other domains (Qualman, 2010; Scott, 2017)). User behaviour, whether individual or social, can be seen as a form of building analysis, ie, how does the building produce the expected behaviours of its occupants. Viewed this way the users' social behaviour fits well into existing design theories as instances of *analysis* to produce *behaviour*, with the user becoming part of the *structure* (in FBS terminology) from which behaviour is derived. The modeling of user behaviour will require methods that are novel in design research, methods from social analytics (Pentland, 2015; Sarkar and Gero, 2017)

4.4. User-building interactions

Currently buildings are designed without taking any or only a minimal account of the interactions of the user with the building and the building with the user, although there are unique exceptions. This used to mean intelligent buildings, whose services respond to user behaviour and changes in the environment (Nguyen and Aiello, 2013). More recently the facades of some buildings change shape based on their interactions with their environments. Today interactions cover both the building and the Building Internet of Things (BIoT), where both the building fabric and fitments are all capable of interacting and responding by being connected to the internet (Atzori et al, 2014; Li and Yu, 2011). Designing for such interactions will require new knowledge about component capabilities and interaction processes but these fit well into *structure* and *behaviour* in design theories. Current design methods can encapsulate these interactions within the methods used for determining behaviour of a building using different knowledge to produce the behaviour, so no new design methods would be required.

4.5. User emotions

Currently there is little if any account taken formally of the emotional response of building users in the design process. This is surprising given that architecture distinguishes itself from building by being concerned with the emotional response to space and form (delight) as well as utility (commodity and firmness), whilst building is only concerned with utility. We can expect, in the near future, that methods for the determination of emotional responses will be better developed. Predictive methods for emotional response to space and form such as Kansei (Nagamachi, 1989) and others based on perception, psychometric and physiometric studies of people and designers are likely to be included in the design process (Weber et al, 2002). Emotional response is a *behaviour* derived from the building and fits directly into current design theories. It will require new tools and knowledge to incorporate emotional responses into design processes but does not change the process itself.

4.6. Design tools that learn and adapt

Currently design tools are unaffected by their use, we can expect design tools to learn through their use and to customize themselves to their individual users. Many tools are expected to remain unchanged by their use: for example a spreadsheet should always provide the same answer for the same input. However, for example, it would be useful for a CAD interface to become easier to use the more you use it, ie, it should learn and adapt itself based on the way an individual designer uses it (Gero, 1996; Peng and Gero, 2009). Tools that learn and adapt would have no impact on design theories or design methods as they would improve the efficiency of the tool but not change the fundamentals of the tool itself.

4.7. Buildings that learn and adapt

Currently buildings do not learn about their behavior and use in ways that the knowledge gained can be transferred to designers and other designs. This is because buildings have very few sensors in them and where there are sensors the data is not made available. Elsewhere, vast quantities of data are generated about human behaviour and learning from mining that data. For example, this is the basis of Amazon's recommender system. As the cost of sensors drops it becomes economically feasible to embed a large array of sensors in buildings and to collect data that becomes the foundation of new knowledge which is made available to designers (Chong and Kumar, 2003). The new knowledge is about building behaviour and no changes will be needed to either design theories or design methods, as the new knowledge sits outside both. Currently only a few building adapt to their environment and even fewer if any adapt to the way they are used, we can expect buildings to be designed to adapt, expanding the definition and meaning of "intelligent buildings". There are exemplars of advertising in buildings adapting to the viewer in the movie *Minority Report* (Spielberg, 2002) and of virtual buildings adapting to their use in ActiveWorlds (Maher et al, 2003). Learning and adapting changes the *behaviour* of the design by possibly changing its *structure*, although no change in structure may be required. This is likely to require new design methods that can include the new knowledge supporting the processes for encoding learning and adaptation in the building but existing design theories cover this under *synthesis*.

4.8. Buildings as part of a social ecology

Currently, each building is an individual entity without any interaction with other buildings, we can expect buildings to interact with each other form an ecological network of sensors across buildings. This based on the way that trees turn out to be part of a social ecology by communicating with each other about activities such as insect infestation (Wohlleben, 2016), similarly buildings could communicate with each other about external conditions that affect them to give early warning to other buildings to make remedial responsive changes in time. This requires new design methods but in terms of design theories it fits well into behaviour, so no changes in design theory would be required to include this.

4.9. Brain-computer interface, user-building interface and brain-building interface

The concept of a brain-computer interface was introduced in 1973 (Vidal, 1973) and we can expect this to become available as a means of both designing and using a building (Liu et al, 2016; Nicolas-Alonso and Gomez-Gil, 2012). As the computer becomes more fully integrated into design, brain-computer interfaces will bypass many current interfaces. In 2010 commercial brain-computer interface systems demonstrated controlling virtual objects in a CAD-like environment by thoughts in the brain alone, Figure 2. It is unclear whether progress in this area will result in the externalization of the more intellectual activity that designing entails (Alexiou et al, 2010). If it is does then we may have re-examine current design theories, certainly it will result in new design methods.

(a) (b) (c) (d)

Figure 2: Images from Le's TED talk (Le, 2010). (a) EEG headset on user, (b) orange cube as object to be controlled by thought alone, (c) result of thinking of bringing cube closer, and (d) result of thinking of making cube disappear.

The physiology of the user can now be measured using biometric technologies developed for the security industry (Jain et al, 2004) and this provides a new kind of user-building interface that would allow the building to respond directly to users. There is already mobile brain scanning equipment that could be used as the basis of a brain-building interface. These novel interfaces do not change designing, they introduce new behavioural responses in the building and may require new design methods.

5. Conclusion

This position paper has examined nine possible changes to designing and to buildings based on new knowledge or new technology within the framework of assessing whether design theories or design methods will need to be changed to cover them. It looked at potential changes in our knowledge about the cognitive behaviour of designers, users, users' social behaviour, user-building interactions, user emotions, design tools that learn and adapt, buildings that learn and adapt, buildings as part of a social ecology, and three new types of interfaces: brain-computer interfaces, user-building interfaces and brain-building interfaces. It assessed whether each of these could be fitted into current design theories. In all but one case it found that these changes could fit within many of current design theories and as a consequence no modifications or extensions would be required to make use of the new knowledge or new technology to describe and model designing. However, new design methods would need to developed to make use of this new knowledge and new technology. This points to where design methods research should focus.

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